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Palaeomagnetic investigations of sediments cores from Axios zone (N. Greece): implications of low inclinations in the Aegean

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Abstract. Sediment cores from 13 deep boreholes (1–4.1 km) distributed within Axios zone in Northern Greece have been studied by means of palaeomagnetism. Both low field magnetic susceptibility and intensity of the natural remanent magnetization (NRM) indicate rather weakly magnetised materials. A set of 390 samples have been subjected to thermal and alternative field demagnetization. Isothermal remanent magnetization (IRM) acquisition curves and thermomagnetic analysis suggest the dominance of magnetite. Thin sections from 30 selected samples were studied in order to more precisely characterise their magnetic mineralogy. This investigation also reveals the presence of magnetite and pyrite in framboidal form. An attempt to re-orient some of the samples was partially successful by using the viscous component and the anisotropy method. These techniques were applied in order to correct the palaeomagnetic directions due to the orientation ambiguity of the core samples. The corrected mean direction converges towards an eastward value, in agreement with the overall pattern of the onshore results from previous investigations in the study area.

Finally, the observed inclinations of characteristic remanences in these rocks are much lower than the expected ones but converge with those obtained from formations on land.

1 Introduction

Numerous palaeomagnetic studies in Greece have contributed to the better understanding of the geotectonic framework of the area and to the establishment of magnetostratigraphic columns (Duermeijer et al., 2000; Kondopoulou 2000, and references therein; Van Hinsbergen et al., 2005). In particular, previous palaeomagnetic studies in various

formations (ophiolites, plutonites, sediments) on and around the Chalkidiki peninsula have revealed the presence of stable magnetization components of different ages (Kondopoulou and Westphal, 1986; Edel et al., 1991; Feinberg et al., 1994; Kondopoulou, 1994; Haubold et al., 1997). These components imply clockwise rotation during Cenozoic, consistent with the general pattern of the Central – Eastern N. Greece. On the other hand, inclination values are usually lower than expected by 5°–20° (Kondopoulou and Westphal, 1986; Kondopoulou et al., 1996; Beck et al., 2001). However, it should be noted that these low inclinations have been observed only at surface outcrops or borehole samples from shallow coring of lake sediments (Papamarinopoulos, 1978). Preliminary results from early palaeomagnetic and rock magnetic investigations from four deep-drill cores (Kass-1, Kass-2, Kass-3, Kass-4) have already been published in a previous paper (Aidona et al., 2001).

In the present study we present palaeomagnetic information from a large number of core samples from 13 deep boreholes (up to 4000 m) that were drilled down by the Greek Petroleum Company for oil exploration. It must be clarified that in these boreholes core sampling is sparse and is limited only on few specific layers of interest. The vast drilling procedure produces only small fragments (“cuttings”). Nevertheless, the dataset which was obtained provides valuable information both on the long-standing problem of the low inclination values and the validity of the rotation pattern of the North – Central Greece.

2 Geological setting and sampling

The study area includes the north (Giannitsa-Thessaloniki plain) and eastern (West Chalkidiki and Kassandra peninsula) margins of Thermaikos gulf. From the geotectonic point of view the area belongs to the Axios zone (internal Hellenides). Mesozoic rocks (limestones, ophiolites) of



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Table 1. Mean values of NRM intensity and magnetic mass susceptibility for all studied cores. Column 2 shows grouping of cores according to their geographical position.

Name	Area	N	Mean Intensity Value (mA/m)	Mean Mass Susceptibility Value (SI 10 ^{−5})
EP-1 (Cores1-2)	Epanomi	10	1.138	18.17
EP-1 (Cores 3-7)		24	0.137	−0.366
EP-2		21	0.081	1.127
EP – B1		36	0.196	−0.113
IRA-2	Epanomi	65	0.012	−0.377
KASS-1	Kassandra	56	2.43	16.1
KASS-2		66	0.88	11.93
KASS-3		59	1.34	14.02
KASS-4		91	1.51	16.26
POS-1	Kassandra	119	5.32	17.92
Kor-2	Axios	26	26.43	28.08
Al-1		14	8.41	15.84
Lo-1		8	0.34	2.97
Nir-1		26	2.68	14.43

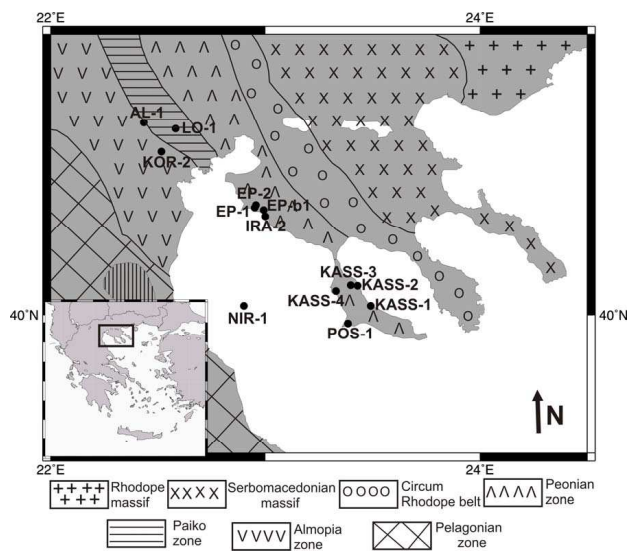


Fig. 1. Schematic map of Chalkidiki Peninsula, whith the location of the studied drill cores shown.

Axios zone form the basement of the area. During Paleogene an extensive NNW-SSE trending trench was formed and filled by Paleogene molassic sediments (sandstones, few limestones), while in Miocene a new NNW-SSE graben was formed again and filled gradually during Neogene-Quaternary by mainly clastic sediments (sands, sandstones, clays, red beds) and few marls and limestones (Antonios Fm, Triglia Fm, Trilofos Fm, Moudania Fm) (Syrides, 1990). At present, basement and Paleogene sediments expose at the mountainous periphery of the Thermaikos gulf while in the low relief hilly area the basement is covered by the Neogene–Quaternary deposits exceeding 4000 m in thickness.

Axios area (drills Kor-2, Al-1, Lo-1) belongs to the Paiko zone. This zone consists of volcano-sedimentary rocks of Upper Jurassic age, a calcareous horizon of the same age and flysch of Low Cretaceous age which is covered by Middle-Upper Cretaceous sediments (Mercier, 1968).

In order to simplify descriptions the sampled cores are grouped into 4 sets according to their position: Axios area (Kor-2, Al-1, Lo-1), Kassandra peninsula (Kass-1,Kass-2,Kass-3,Kass-4, Po-1) Epanomi (Ep-1, Ep-2, Ep-b1, Ira-2) and a submarine core, Nireas-1 (Fig. 1).

The stratigraphy of the drilled cores is rather simple: all 4 groups contain a thick clastic sediment layer, which covers the pre-Neogene basement (Fig. 2). In particular, in the Kassandra set, the clastic layer (Eocene-Miocene) overlays the ophiolite basement. In the Epanomi set the clastic layer of Eocene-Pliocene age covers the Jurassic limestone and in the Axios set the same clastic sediments (Eocene- Pliocene) overlay the Mesozoic metamorphic basement (Georgala, 1990, 1994).

From all these deep boreholes, 621 core samples, cylinders of standard palaeomagnetic size from various depths were obtained. In the laboratory 390 of these samples were demagnetized using thermal and alternating field demagnetization. Tilt values were provided from the Greek Petroleum Company only for Kass-3, and Kass-4 boreholes and suggest limited tilting (<15°) of the samples units, with only few exceptions reaching tilts up to 25°.

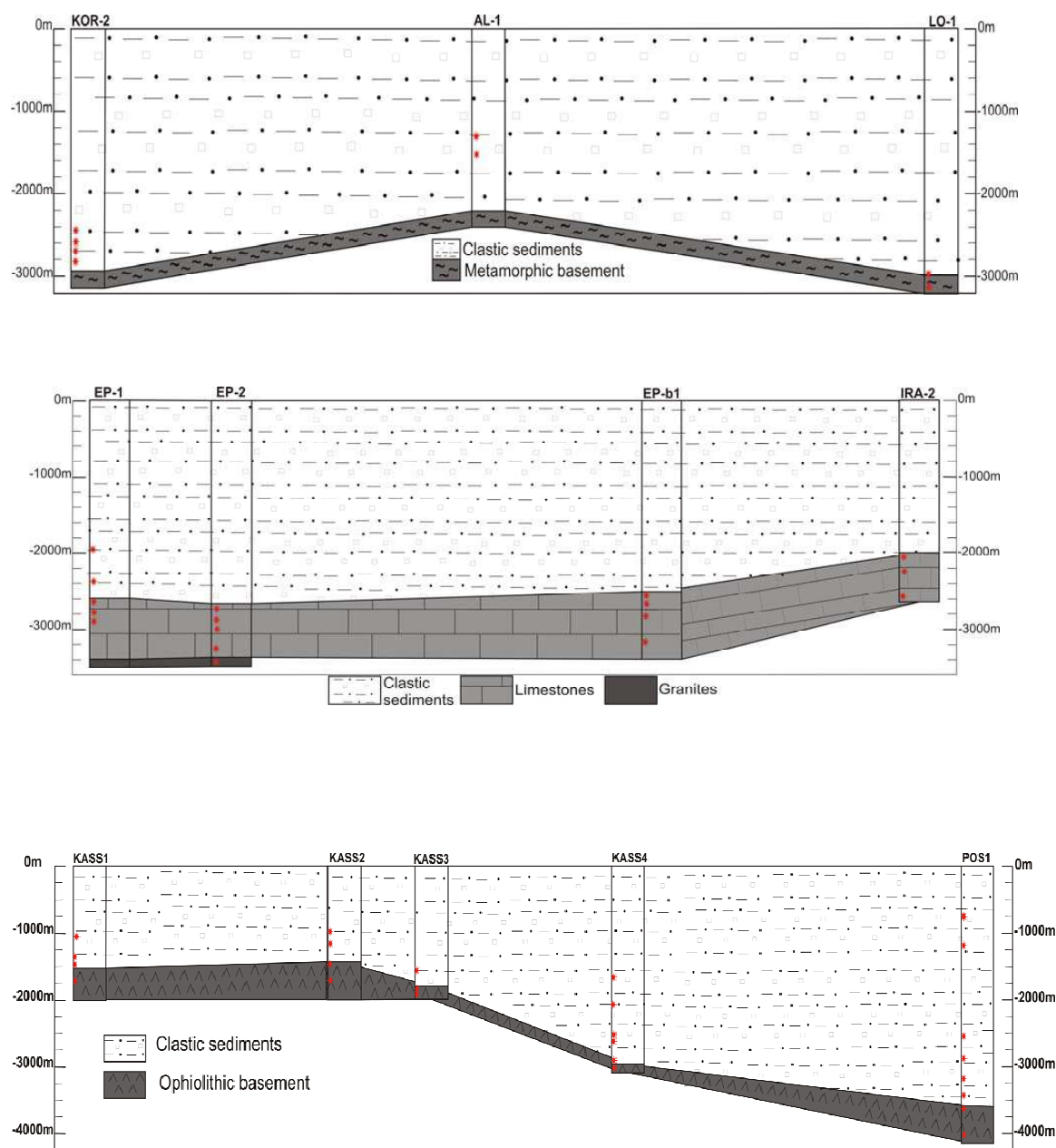


Fig. 2. Lithostratigraphy of all studied cores. Red dots show the depths where drill cores were taken.

3 Laboratory treatment

3.1 Palaeomagnetic measurements

The magnetic low field susceptibility from all 621 specimens was measured with a Bartington MS2 device at low frequency (0.47 kHz). The mean mass susceptibilities as well as the mean NRM intensity values for the 13 boreholes are displayed in Table 1. The mean susceptibility for the samples of Epanomi group shows negative values, which indicate the presence of diamagnetic minerals. The majority of

the other boreholes show a mean susceptibility, ranging from $12\text{--}18 \times 10^{-5}$ units and only Kor-2 gives mean susceptibility values up to 28×10^{-5} units.

The natural remanent magnetization (NRM) of all 621 specimens was initially measured on a Molspin spinner magnetometer. The samples from Epanomi group turned to be very weakly magnetized (around 0.2 mA/m) thus they were measured on a cryogenic magnetometer. All the remaining samples showed higher intensities of magnetization, up to 20 mA/m (Kor-2) (Table 1).

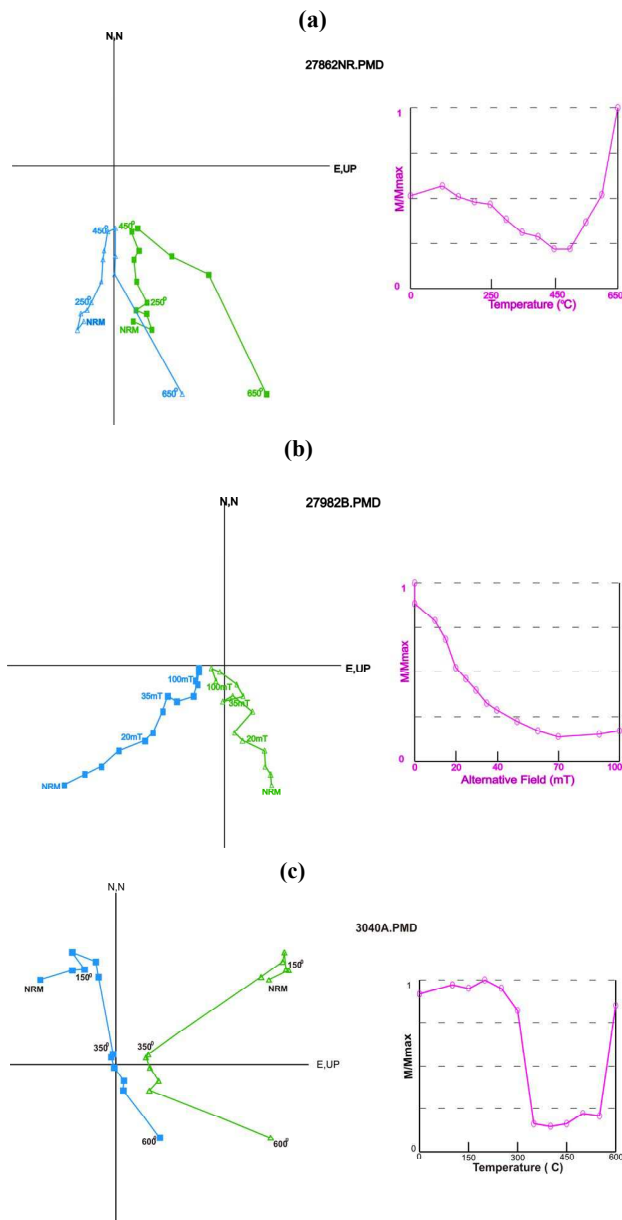


Fig. 3. Zijderveld diagrams and normalized magnetic intensity curves with stepwise AF thermal (a) and AF (b) demagnetization for representative samples. (c) Zijderveld diagram showing the viscous component (NRM to 150°C). Open triangles: projection onto the vertical plan, Black squares: projection onto the horizontal plan.

Magnetic cleaning was performed in 390 specimens by using thermal stepwise (Th) up to 650°C with 50°C step and alternating field (AF) up to 100 mT with 5 mT–10 mT step, demagnetizations.

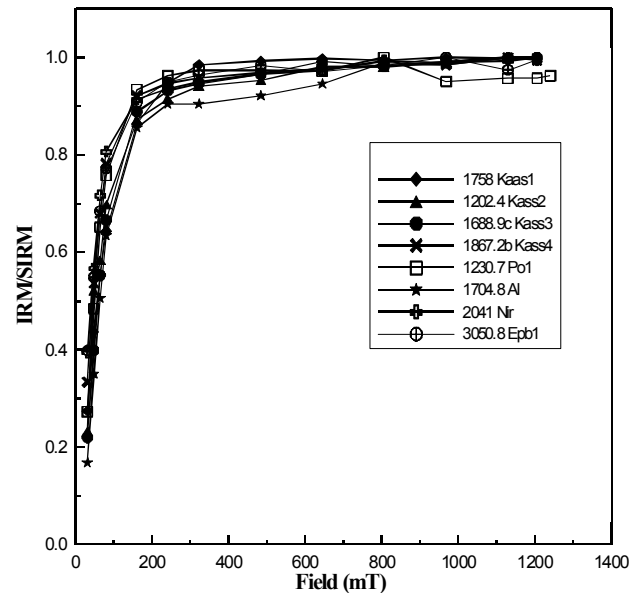


Fig. 4. IRM acquisition curves for representative samples.

3.2 Rock magnetism and mineralogical analysis

Isothermal remanent magnetization (IRM) and thermomagnetic analysis have been performed on 70 specimens for the determination of the magnetic carriers. The IRM was imparted using a pulse magnetizer and was measured on a spinner magnetometer. The majority of the thermomagnetic analyses were performed on a KLY-3 Kappabridge which measures the variation of the magnetic susceptibility with temperature. Only for few samples the Susceptibility Temperature Bartington Device was used.

A set of 30 polished thin sections were prepared and were studied by reflected light microscopy under high magnification, in order to investigate the distribution of the minerals into the samples. The morphology of the minerals was studied by a GEOL-840A Scanning Electron Microscope, equipped with a LINK ISIS microanalyzer and using carbon coated samples.

4 Results

The majority of the samples from Kassandra and Axios areas were weakly magnetized but stable components have been isolated in most cases. The thermal stepwise demagnetization has been successful up to 400°C–450°C. Above this temperature, the intensity of the magnetization consistently increased in the majority of the samples (Fig. 3a). This behavior is probably related to alteration (oxidation) of pyrite, which is present in all samples and to the formation of new parasitic minerals which overlap the high coercivity component of magnetization of the samples. Thus, the high

temperature component has been lost and only a stable component (between 200°–450°C) has been isolated. On the contrary, the AF demagnetization process proved to be more successful for the determination of the magnetic components, since during the AF procedure generation of new parasitic minerals is avoided (Fig. 3b). Therefore, the characteristic component of magnetization was possible to isolate in most of the samples in fields between 20–80 mT. The thermal and AF demagnetizations were performed in twin specimens, so the high coercivity component calculated by AF was used as a reference for checking the stable direction obtained through the thermal procedure. The criteria used to decide whether or not a direction would be considered as reliable were: a) a smooth decay curve, b) no variation of susceptibility during heating, c) alignment of at least 4 points, and e) a reliable a_{95} value ($<15^\circ$). The characteristic directions of the magnetization were determined by least squares fitting (Principal Component Analysis) through selected points. All samples from Epanomi area were rejected due to their extremely low intensity of magnetization.

IRM measurements reveal the dominance of magnetite as the main magnetic carrier in most of our samples (Fig. 4). Many samples achieve their saturation remanence in fields of 200–300 mT. In few cases the saturation is not reached up to 1200 mT, thus indicating the presence of hematite. Thermomagnetic analysis confirms the dominance of magnetite, as the maximum blocking temperature reaches 580°C in most of the cases. It is also clear that during the heating, secondary magnetite is formed (Fig. 5).

Finally, the study of the thin sections confirms the presence of magnetite, hematite and pyrite and reveals the presence of ilmenite and chromite (Fig. 6). Magnetite is considered as a detrital mineral coming from the surrounding igneous and metamorphic rocks deposited in the sedimentary basin. Pyrite microcrysts appear mainly in the framboidal form but clouds of pyrite microcrysts not organized in framboids are also present (Fig. 6). The framboids are usually found in colonies, filling, in some cases, fossils of micro-organisms (Fig. 6). The presence of framboidal pyrite is attributed to low temperature and neutral to alkaline pH values. These conditions reduce pyrite solubility and are essential for the formation and following preservation of the framboids (Rickard, 1969, 1970).

5 Re-orientation of cores

In order to derive palaeomagnetic results from cores it is necessary, as a first step, to bring back core pieces into their initial position with respect to north and to vertical. For this reason, in the last decades, a number of new techniques of re-orientation of cores have been developed, and, among others, the palaeomagnetic reorientation. This method is based on the isolation of the viscous component of the magnetization which records the direction of the present geomagnetic field

(Fuller, 1969; Van der Voo and Watts, 1978; Shibuya et al., 1991; Hailwood and Ding, 1995). According to this method we isolated the viscous component from our samples but as it is shown in a stereographic projection in Fig. 7 the majority of the samples show very shallow inclination values. This fact leads us to the conclusion that it is impossible to use these values in order to re-orient our cores. It is likely that a parasitic magnetization created during storage in horizontal position of the samples for several years (Athens storage center) had affected the samples and lead to the destruction of their viscous component of the magnetization. Samples from Axios cores seem to be an exception (Figs. 3c, 8). As these samples were stored in another stockroom (Kavala storage center), they have obviously not been affected by the same parasitic magnetization.

Regarding the position of the cores with respect to the vertical, the method of anisotropy of the magnetic susceptibility was applied (Hailwood and Ding, 1995). By measuring the anisotropy of magnetic susceptibility we could determine the plane of k_{ax} and k_{int} and the position of the k_{min} axis of anisotropy. For a sedimentary sequence which was deposited in an undisturbed environment, the k_{min} axis would be perpendicular to the bedding plane (Hamilton and Rees, 1970; Tarling and Hrouda, 1993). Measurements of anisotropy of the magnetic susceptibility were performed on 120 specimens, with a KLY-3 Kappabridge and the results are shown in Fig. 9. Only specimens with values of magnetic foliation higher than 1.010 were considered reliable and among these, samples with k_{min} inclination values (blue circles) less than 75° were corrected. Thus, a small set of samples (10% of the total) with corrected declination and inclination values was derived (Fig. 10). A large dispersion is observed for both declination and inclination values but within reasonable limits of reliability. Nevertheless, some general trends can be safely recognized and will be discussed in the next paragraph.

6 Discussion

In spite of the generally weak magnetizations the careful palaeomagnetic and rock magnetic studies of the cores were successful in isolating stable components in most cases. The obtained magnetic parameters can be exploited mostly as far as the inclination values are concerned. In Table 2 all the obtained results from this study are presented. The criteria used for the acceptance or rejection of the samples, are based on inclination values, a_{95} values and the number of specimens measured from every core sample. It is important to notice that the final grouping of the results was based on their age distribution.

A mean inclination was computed using the method of Enkin and Watson (1996), which disregards all declination data. Inclination values have been compiled for the Eocene-Oligocene and separately for the basement (Table 2).

Table 2. Obtained results from the present study. Name=name of the borehole, I =inclination value, a_{95} =uncertainty, k =Fisher's precision parameter, n =number of specimens, Age=age of the samples (see in the text for details).

Name	I	a_{95}	k	n	Age
Kass-1					
1117–1120	10.8°	4.3°	73	12	Eocene
1160	23.1°	40.9°	165	3	Eocene
1190	3.6°	42.3°	155	3	Eocene
1443	27.3°	40.4°	9	3	Eocene
1544–1547	31.8°	11.5°	22	7	Eocene
1758	24.6°	12.6°	53	4	Basement
Kass-2					
1133–1140	30.8°	10.9°	11	13	Eocene
1198–2005	23.8°	9.7°	17	11	Eocene
1464	39.3°	–	6	3	Eocene
Kass-3					
1688–1694	33.7°	9.2°	12	16	Eocene
1867–1869	38.5°	39.8°	4	5	Basement
1971–1974	35.3°	17.3°	8	8	Basement
Kass-4					
1863–1869	21.8°	11.1°	13	11	Oligocene
2328–2335	23.6°	16.5°	8	9	Oligocene
2650–2655	77.1°	4.0°	1348	5	Eocene
2796–2804	46.4°	12.8°	18	7	Eocene
2902–2908	71.9°	9.4°	59	5	Eocene
3040–3043	20.0°	14°	19	6	Basement
Pos-1					
1225–1231	28.1°	11.4°	11	12	Oligocene
2642–2648	24.8°	12.1°	8	14	Oligocene
3027–3032	26.9°	23.9°	6	7	Oligocene
3287–3290	64.0°	13.5°	26	6	Eocene
3467–3472	62.5°	8.0°	29	10	Eocene
4116–4118	38.3°	19°	15	5	Basement
Kor-2					
2704–2705	74.5°	24.9°	34	4	Eoc-Olig
2742–2787	73.3°	8.1°	82	5	Eoc-Olig
2796–2798	48°	12.9°	10	11	Eoc-Olig
Nir-1					
2041–2047	30.2°	25.7°	13	4	Oligocene
2785–2787	19°	12.6°	53	4	Oligocene
3563–3567	65°	5.3°	48	13	Eocene
Al-1					
1623–1626	27.1°	18.3°	11	6	Eoc-Olig
1700–1704	53.2°	19.6°	7	8	Eoc-Olig
Lo-1					
3011–3015	48.4°	46.8°	3	5	Basement

Table 3a. Published palaeomagnetic data from the onshore formations for the broader area.

Area	Formation	Age	<i>N</i>	<i>D</i>	<i>I</i>	<i>A</i> ₉₅	Reference
1. Chalkidiki (Kassandra)	Sediments	Mio-Pliocene	9	24.7	54.2	5	Haubold et al. (1999)
2. Axios	Sediments	Miocene	4	20	46	17	Aidona et al. (1996); Sen et al. (2000)
3. Strimonikos	Plutonics	Oligocene-Miocene	2	026	47	–	Westphal et al., (1991)
4. Chalkidiki (Paliouri)	Sediments	Eocene- Oligocene	4	220.2	–47.3	–	Feinberg et al. (1994)
5. Chalkidiki (Sithonia-Ouranoupoli)	Plutonics	Eocene- Oligocene	8	037	31	9	Kondopoulou and Westphal (1986)
6. Axios (Oreokastro)	Plutonics	Eocene	1	29.5	39	–	Feinberg et al. (1994)
7. Axios (Goumenissa)	Plutonics	Eocene	1	89	49	14	Feinberg et al. (1994)
8. Chalkidiki (Paliouri)	Sediments	Jurassic	9	32.1	50	18	Feinberg et al. (1994)
9. Chalkidiki	Ophiolites	Jurassic	5	314	34	13	Edel et al. (1991)
10. Axios – Chalkidiki	Ophiolites	Jurassic (?)	16	318,7	36,5	9,5	Feinberg et al. (1996)
11. Chalkidiki (Monopigado)	Granites	Jurassic	1	56.5	25	16	Feinberg et al. (1996)
Expected declination and inclination values for the area							
Kassandra		Eocene		10.1	53.9		Besse and Courtillot (2002)
Kassandra		Oligocene		10.3	56.1		Besse and Courtillot (2002)

Table 3b. Published palaeomagnetic data from the Mesohellenic basin.

Area	Age	<i>N</i>	<i>D</i>	<i>I</i>	<i>k</i>	<i>A</i> ₉₅	Reference
Mesohellenic Basin EE (mean)	Oligocene-M.Miocene	6	51.7	28.2	19.5	15.5	Van Hinsbergen et al. (2005)
Mesohellenic Basin EE (mean)	Eocene – Oligocene	4	65.4	39.1	15.3	24.3	Van Hinsbergen et al. (2005)
Mesohellenic Basin DD (mean)	Oligocene – M.Miocene	8	51.0	20.3	25.8	11.1	Van Hinsbergen et al. (2005)
Mesohellenic Basin Krania (mean)	L. Eocene	6	46.4	19.5	27.2	13.1	Van Hinsbergen et al. (2005)
Mesohellenic Basin SM (mean)	36–24Ma	5	27.0	47.0	16.0	10.0	Kissel and Laj (1988)

Results are as follows: $I=32.9^{+5.6}_{-5.6}$, $\kappa=10$, for the Oligocene, $I=44.3^{+5.2}_{-4.7}$, $\kappa=9$ for the Eocene and $I=31.1^{+7.9}_{-6.9}$, $\kappa=10$ for the ophiolite basement (Jurassic?).

Inclination data from an allochthonous ophiolite cannot be interpreted unless the palaeohorizontal can be determined. This is practically impossible for drill core materials. In order to overcome this difficulty and properly evaluate the observed inclination values, we have compiled all published data from onshore formations from the broader area (Table 3a). The general agreement of inclination values from the two datasets is supported by one particular case. Palaeomagnetic results from ophiolites and associated sediments in the edge of Kassandra peninsula yield a direction with $D=325.4^\circ$ and $I=34.1^\circ$ for the Mesozoic component (Feinberg et al., 1996). Given that in this case the palaeohorizontal was unambiguously determined, it is clear that this inclination value (34.1°) can be used as a reference value for inclination data from the neighboring area.

In Fig. 11 the distribution of inclination values for Kassandra area is shown. It is observed that Eocene inclination values for drill cores Kass-4 and Pos are much higher than for the other boreholes. This difference indicates the presence of local intense tectonic events (fast block tiltings) during the end of Eocene. This fact is in good agreement with the formation of the sedimentary basin and its rapid extension

after Middle Eocene as confirmed by the sedimentological study (Roussos, 1994). If we extend the broader area to a largest one, up to the western edge of the Pelagonian zone a small dataset with published directions (Table 3b) displays a range of inclinations comparable with the low inclinations calculated in the present study but divergent from the observed high inclinations in the two drill cores Kass-4 and Pos. Also, the eastern part of the study area (Sithonia and central Chalkidiki) gives similar low inclination results for Eo-Oligocene plutonic formations ($I=31^\circ$) (Kondopoulou and Westphal, 1986). Therefore, it can be derived that the overall inclination is low and the high inclinations in Kass-4 and Pos are strictly limited to the internal part of the Thermaikos gulf, possibly due to local tectonism related to the formation of the adjacent graben.

The expected inclination values computed from the European apparent polar wander path are or $53,7^\circ$ for the Eocene and 54° for the Oligocene (Besse and Courtillot, 2002). Taking these values into account the observed inclination values are consistently low ($31^\circ/44^\circ$) for Eocene-Oligocene formations or Eocene overprints (Table 3a). The comparison of the on-shore and borehole samples clearly shows that inclination values are compatible and much lower than the expected values (by $\sim 20^\circ$). A smaller dataset, comprising results from reoriented borehole samples from the present study (Fig. 10) should be examined with due care. In this

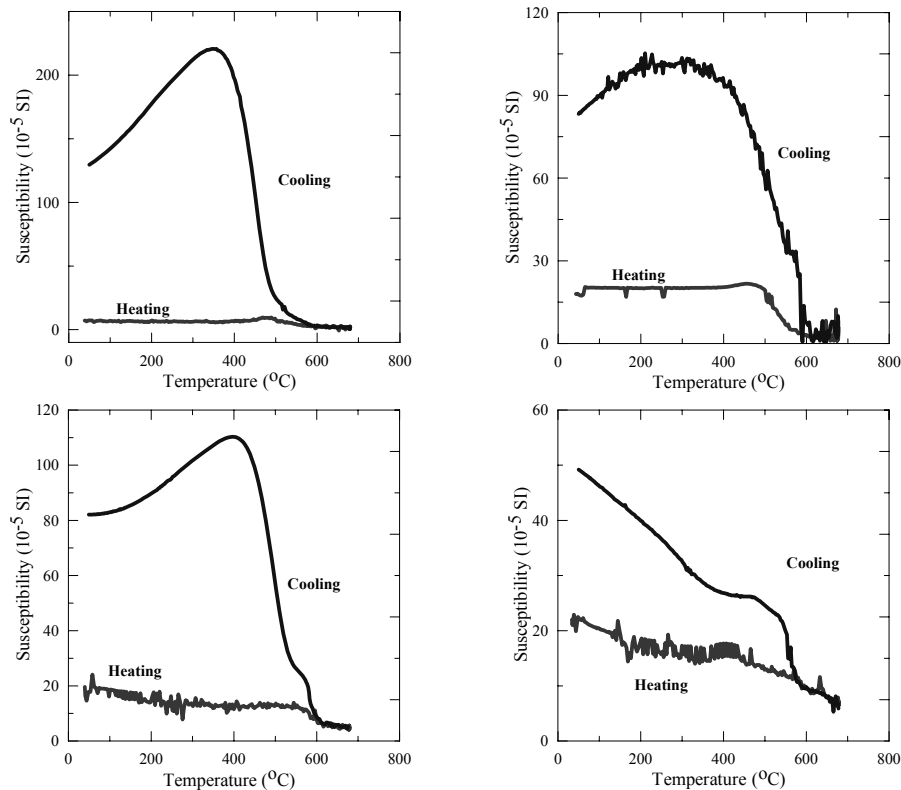


Fig. 5. Thermomagnetic analysis indicating the presence of magnetite and the transformation of low susceptibility to high susceptibility minerals during cooling.

small group ($N=25$) the mean declination value is in a good agreement with almost all published on-shore results for the broader Chalkidiki area (Table 3a). As far as the inclination values are concerned, their mean ($I=58.2^\circ$) is close to the expected one for the area and the Eocene-Oligocene period. At a first approach this could be in contradiction with the generally lower inclination values measured in the present study but also in the published on-shore data. This divergence is not determinative since the data used for the reorientation are derived from the cores Kass-4, Pos-1 and Kor-2 where high inclination values prevail. Therefore, the mean inclination value for reoriented samples is shifted to a higher range. For all these reasons, we consider as representative the inclinations obtained from the totality of the studied samples.

The problem of low inclinations for the Cenozoic formations in the broader Aegean area has been widely discussed (Kissel and Laj, 1988; Van der Voo, 1993; Beck and Schermer, 1994; Beck et al., 2001; Kissel et al., 2003). The thorough examination of this problem by Beck et al. (2001) led to the suggestion of a NW motion of the Aegean block by ~ 500 Km with respect to N. Europe, which cannot be supported by geological data. In their discussion on shallow inclinations in the Aegean realm, Kissel et al. (2003) conclude that the problem is not fully understood. A different approach used by Krijgsman and Tauxe (2004) based on the

“elongation/inclination” method of Tauxe and Kent (2004), led the authors to the suggestion that an inclination error is the main responsible for low inclinations in sedimentary formations and inappropriate tilt corrections for the ones observed in lava flows in the area. This last assumption is based on the Beck et al. (2001) study of volcanic rocks in Lesbos island. As far as the sediments are concerned their conclusion seems realistic and converges with the one of Kissel et al. (2003). On the other hand, we believe that “inappropriate tilt” is a very simplistic approach for lavas, as similar low inclinations in volcanics, have been reported from other Oligo-Miocene formations in the broader Aegean (Kissel et al., 1986 a,b; Morris, 1995; Haubold et al., 1997; Morris, 2000). It is difficult to consider that in such a broad dataset, obtained by different groups and with various sampling techniques, a systematic error in applying tilt corrections has occurred.

Several studies have revealed the same anomalous inclinations further to the region of central Asia (Hankard et al., 2007 and references therein). Chauvin et al. (1996) proposed that inclination anomaly progressively increases from 0° on the Atlantic margin to about 10° in the eastern Mediterranean and Middle East to reach maximum of 25° in central Asia, due to a regional non-dipole field. Si and Van der Voo (2001) proposed that the large discrepancies between observed and

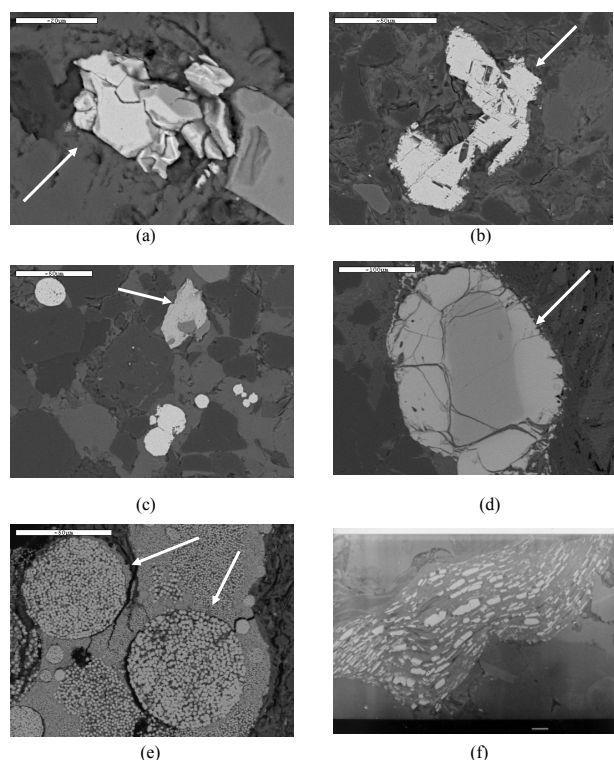


Fig. 6. (a) Scanning electron micrograph of a magnetite crystal, (b) Scanning electron micrograph of an hematite crystal, (c) Scanning electron micrograph of an ilmenite crystal, (d) Scanning electron micrograph of chromite crystal, (e) Backscattered electron micrograph showing framboids in colonies, surrounded by a thin surface membrane, (f) Scanning electron micrograph showing pyrite microcrystals of different size, not organized in framboids.

predicted palaeolatitudes in Asia during latest Cretaceous and Tertiary can be explained by the contribution of a long-term non-dipole field to the total time-averaged geomagnetic field. Finally Van der Voo and Torsvik (2001) suggested that an octupole field may have been responsible for the palaeolatitude anomalies in central Asia, adopting the earlier suggestion by Westphal (1993).

Additionally, if the Eocene alternative pole for Eurasia suggested by Westphal (1993) is taken into account ($I_{\text{exp}} \sim 35^\circ$) a satisfactory match is observed with the inclination values reported here, suggesting that large-scale crustal displacements are unnecessary for this geological period.

In the present study, as the on-shore literature data come mostly from plutonic rocks and are in good agreement with data from the borehole samples (both have shallow inclinations), we consider that inclination flattening does not contribute significantly to the observed inclination anomalies.

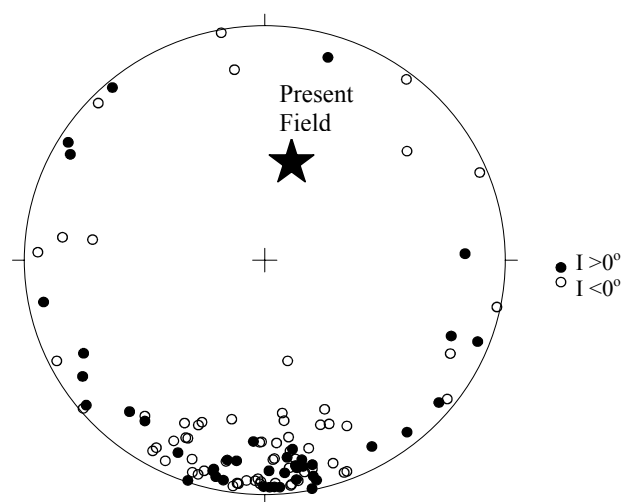


Fig. 7. Stereographic projection (lower hemisphere) of the isolated viscous component of the samples showing very shallow inclination values. Geographical coordinates correspond only to the present field direction, all other data are in specimen coordinates.

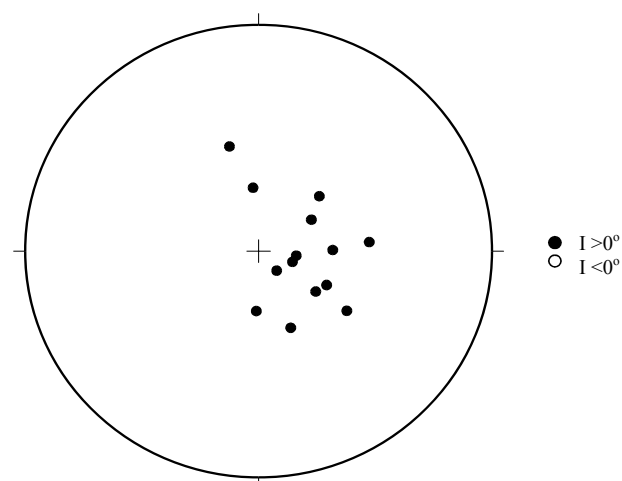


Fig. 8. Equal area projection, lower hemisphere showing the viscous component of Axios samples. All data are in specimen coordinates.

7 Conclusions

The study of drill sediment cores from Axios zone provided a set of meaningful results for an area and a time span in which such data are very scarce (Eocene – Oligocene).

In the case of Epanomi samples, possible dolomitization could have affected these sediments, leading to their remagnetization. As a result the total magnetic grains were replaced by diamagnetic ones destroying the remanent magnetization of the samples.

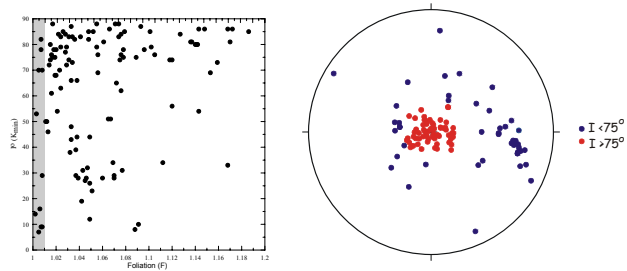


Fig. 9. Inclination values versus foliation (left) and equal area projections (lower hemisphere) of the direction of K_{\min} axis of anisotropy of the samples (right), in specimen coordinates.

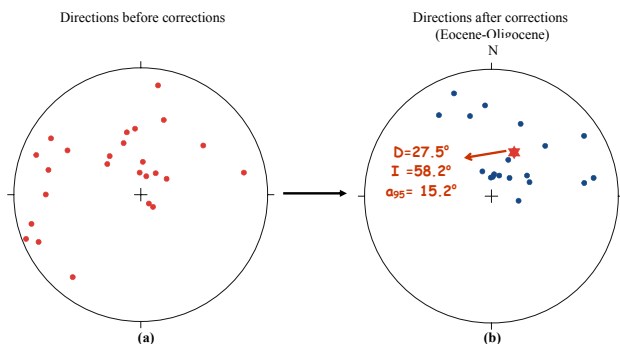


Fig. 10. Equal area projection (lower hemisphere) of (a) initial directions of the samples before the reorientation, in specimen coordinates, (b) final directions after the corrections, in stratigraphic coordinates. Red star represents the mean direction of these samples.

The usage of the viscous component of the magnetization for the correction of declination proved to be impossible due to storage effect. Only in few cases the method was applied successfully and reorientation of declination (for these specific samples) was possible. The reorientation procedure might have proved more successful if data from the totality of the boreholes could be used.

The calculated mean inclination values seem to be in good agreement with the overall pattern of inclinations of the broader area from the on-shore formations. The total set of inclination values is lower than the expected ones following the magnetic pole of Eurasia.

The observed low inclinations in plutonic rocks and sediments in previously studied on-shore formations, in combination with the results from the present study lead us to conclude that it is difficult to accept the sediment compaction as the dominant mechanism for low inclination. For the particular time range (Eocene-Oligocene) the alternative pole of Westphal (1993) could possibly give a satisfactory interpretation.

Nevertheless, the overall problem of shallow inclinations in the Aegean area remains still an open issue. Additional

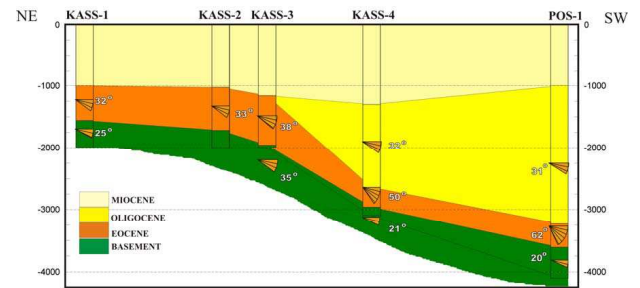


Fig. 11. Distribution of inclination values for Kassandra area. Orange funs represent the inclination values.

data from well-dated volcanic rocks of similar ages with severe control on stratigraphic corrections would be welcomed in order to elucidate the problem.

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References

- Aidona, E., Kondopoulou, D., Koufos, G. and Sen S.: Magnetostratigraphy of late Miocene continental deposits in the Lower Axios Valley (Greece), 1st Congress of the Balkan Geophysical Society, Athens, 1996.
- Aidona E., Kondopoulou, D., and Georgakopoulos, A.: Palaeomagnetic and rock magnetic properties of sediments cores from Chalkidiki, Greece, *Phys. Chem. Earth*, 26(11-12), 879–884, 2001.
- Beck, M. Jr. and Schermer, E.: Aegean palaeomagnetic inclination anomalies: Is there a tectonic explanation?, *Tectonophysics*, 231, 281–292, 1994.
- Beck, M. E., Burmester, R. F., Kondopoulou, D. P., and Atzemoglou, A.: The palaeomagnetism of Lesbos, NE Aegean, and the eastern Mediterranean inclination anomaly, *Geophys. J. Int.*, 145, 233–245, 2001.
- Besse, J. and Courtillot, V.: Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. Geophys. Res.*, 107, 2300, doi:10.1029/2000JB000050, 2002.
- Chauvin, A., Perroud, H., and Bazhenov, M. L.: Anomalous low palaeomagnetic inclinations from Oligocene-Lower Miocene red beds of the southwest Tien Shan, Central Asia, *Geophys. J. Int.*, 126, 303–313, 1996.

- Duermeijer, C. E., Nyst, M., Meijer, P. T., Langereis, C. G., and Spakman, W.: Neogene evolution of the Aegean arc: palaeomagnetic and geodetic evidence for a rapid and young rotation phase, *Earth Planet. Sci. Lett.*, 176, 509–525, 2000.
- Edel, J. B., Kondopoulou, D., Pavlides, S., and Westphal, M.: Multiphase paleomagnetic evolution of the Chalkidiki ophiolitic belt, Greece, Geotectonic implications, *Bull. of the Geol. Soc. of Greece*, 25, 370–392, 1991.
- Enkin, R. J. and Watson, G. S.: Statistical analysis of palaeomagnetic inclination data, *Geophys. J. Int.*, 126, 495–504, 1996.
- Feinberg, H., Kondopoulou, D., Michard, A., and Mountrakis, D.: Paleomagnetism of some northern Greece ophiolites and associated sediments, *Bull. of the Geol. Soc. of Greece* 30, 359–370, 1994.
- Feinberg, H., Edel, B., Kondopoulou, D., and Michard, A.: Implications of ophiolite palaeomagnetism for the interpretation of the geodynamics of Northern Greece, In: Morris, A., Tarling, D.H. (eds), *Palaeomagnetism and Tectonics of the Mediterranean region*, Geological Society of London, Special Publication 105, 289–298, 1996.
- Fuller, M.: Magnetic orientation of borehole core, *Geophysics*, 34, 772–774, 1969.
- Georgala, D.: Sedimentological study of the borehole Kass4, Public Petroleum Company, Internal Report, 1990.
- Georgala, D.: Sedimentological study of the boreholes Kass1, Kass2, Kass3, Public Petroleum Company, Internal Report, 1994.
- Hailwood, E. A. and Ding, F.: Palaeomagnetic reorientation of cores and the magnetic fabric of hydrocarbon reservoir sands, in: *Palaeomagnetic Applications in Hydrocarbon Exploration*, edited by: Turner, P. and Turner, A., Geological Society, London, Special Publications, 98, 245–258, 1995.
- Hamilton, N. and Rees, A. I.: The use of magnetic fabric in paleo-current estimation, In: *Palaeogeophysics*, edited by: Runcorn, S. K., Academic Press, London, 445–464, 1970.
- Hankard, F., Cogne, J.-P., Kravchinsky, V. A., Carporzen L., Bayasgalam, A., and Lkhagvadorj, P.: New Tertiary Palaeomagnetic poles from Mongolia and Siberia at 40,30,20 and 13 Ma: clues on the inclination shallowing problem in central Asia, *J. Geophys. Res.*, 112, B02101, doi:10.1029/2006JB004488, 2007.
- Haubold, H., Scholger, R., Kondopoulou, D., and Mauritsch, H. J.: New palaeomagnetic results from the Aegean extensional province, *Geologie en Mijnbouw*, 76, 45–55, 1997.
- Haubold, H., Kondopoulou D., Scholger R., and Mauritsch H. J.: Further palaeomagnetic evidence for the structural unroofing of the Rhodope metamorphic core complex, Abstract in EGS99, 1999.
- Kissel, C., Kondopoulou, D., Laj, C., and Papadopoulos, P.: New paleomagnetic data from Oligocene formations of Northern Aegean, *Geophys. Res. Lett.*, 13(10), 1039–1042, 1986a.
- Kissel, C., Laj, C., and Mazaud, A.: Paleomagnetic results from Neogene formations in Evia, Skyros and the Volos region and the deformation of Central Aegean, *Geophys. Res. Lett.*, 13, 1446–1449, 1986b.
- Kissel, C. and Laj, C.: The tertiary geodynamic evolution of the Aegean arc: a palaeomagnetic reconstruction, *Tectonophysics*, 146, 183–201, 1988.
- Kissel, C., Laj, C., Poisson, A., and Gorur, N.: Paleomagnetic reconstruction of the Cenozoic evolution of the Eastern Mediterranean, *Tectonophysics*, 362, 199–217, 2003.
- Kondopoulou, D. and Westphal, M.: Paleomagnetism of the Tertiary intrusives from Chalkidiki, N. Greece, *J. Geophysics*, 59, 62–66, 1986.
- Kondopoulou, D.: Some constraints on the origin and timing of magnetization for Mio-Pliocene sediments from N. Greece, *Bull. of the Geol. Soc. of Greece*, XXX/5, 53–66, 1994.
- Kondopoulou, D., Atzemoglou, A., and Pavlides, S.: Palaeomagnetism as a tool for testing geodynamic models in the North Aegean: convergences, controversies and a further hypothesis, in: *Palaeomagnetism and Tectonics of the Mediterranean Region*, edited by: Morris, A. and Tarling D. H., Geological Society, London, Special Publications 105, 277–288, 1996.
- Kondopoulou, D.: Palaeomagnetism in Greece: Cenozoic and Mesozoic components and their geodynamic implications, *Tectonophysics*, 326, 131–151, 2000.
- Krijgsman, W. and Tauxe, L.: Shallow bias in Mediterranean paleomagnetic directions caused by inclination error, *Earth Planet. Sci. Lett.*, 222, 685–695, 2004.
- Mercier, J.: Etude géologique des zones Internes des Hellenides en Macédoine centrale (Grèce), Contribution à l'étude du métamorphisme et de l'évolution magmatique des zones internes des Hellenides, These, Paris 1966, *Ann. Geol. Pays Hellen.*, 20, 1–792, 1968.
- Morris, A.: Rotational deformation during Palaeogene thrusting and basin closure in eastern central Greece: palaeomagnetic evidence from Mesozoic carbonates, *Geophys. J. Int.*, 121, 827–847, 1995.
- Morris, A.: Magnetic fabric and paleomagnetic analyses of the Plio-Quaternary calc-alkaline series of Aegina Island, South Aegean volcanic arc, Greece, *Earth Planet. Sci. Lett.*, 176, 91–105, 2000.
- Papamarinopoulos, S.: Limnomagnetic studies on Greek sediments, PhD Thesis, Univ. of Edinburgh, 94 pp., 1978.
- Rickard, D. T.: The chemistry of iron sulfide formation at low temperature. *Stockholm Contr. Geology*, 20, 67–95, 1969.
- Rickard, D. T.: The origin of framboids, *Lithos*, 3, 269–293, 1970.
- Roussos, N.: Stratigraphy and paleogeographic evolution of the Paleocene molassic basins of the North Aegean area, *Bull. of the Geol. Soc. of Greece*, XXX/2, 275–294, 1994.
- Sen, S., Koufos, G., Kondopoulou D., and de Bonis, L.: Magnetostratigraphy of Late Miocene continental deposits of the Lower Axios valley, Macedonia, Greece, *Geol. Soc. of Greece, Special Publ.* 9, 197–206, 2000.
- Si, J. and Van der Voo, R.: Too-low magnetic inclinations in central Asia: an indication of a long-term Tertiary non-dipole field?, *Terra Nova*, 13, 471–478, 2001.
- Shibuya, H., Merrill, D. L., Hsu, V., and Leg 124 Shipboard Scientific party: Paleogene counterclockwise rotation of the Celebes Sea- orientation of ODP cores utilizing the secondary magnetization, in: Silver, E. A., Rangin, C., von Breyman, M. T. (Eds.) *Proceedings of the Ocean Drilling Program, Scientific Results*, 124, 519–523, 1991.
- Syrides, E. G.: Lithostratigraphic, biostratigraphic and palaeogeographic study of the Neogene-Quaternary sedimentary deposits of Chalkidiki peninsula, Macedonia, Greece, PhD Thesis, University of Thessaloniki, 243 pp., 1990.
- Tarling, D. H. and Hrouda F.: *The Magnetic Anisotropy of Rocks*, Chapman and Hall, 217 pp., 1993.
- Tauxe, L. and Kent D. V.: A new statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic

- inclinations: was the ancient magnetic field dipolar?, in : Timescales of the Internal Geomagnetic Field, edited by: Chan-
nell, J.E.T., Kent, D. V., Lowrie, W., and Meert, J., Geophysical
Monograph, 145, 101–116, 2004.
- Van Hinsbergen, D. J. J., Langereis, C. G., and Meulenkamp, J. E.:
Revision of the timing, magnitude and distribution of Neogene
rotations in the western Aegean region, *Tectonophysics*, 396, 1–
34, 2005.
- Van der Voo, R. and Watts, D. R.: Palaeomagnetic results from ig-
neous and sedimentary rocks from Michigan Basin borehole, *J.*
Geophys. Res., 83, 5844–5848, 1978.
- Van der Voo, R.: Palaeomagnetism of the Atlantic, Tethys and Ia-
petus Oceans, Cambridge Univ. Press, 421 pp., 1993.
- Van der Voo, R. and Torsvik, T. H.: Evidence for Late Paleozoic
and Mesozoic non-dipole fields provides an explanation for the
Pangea reconstruction problems, *Earth Planet. Sci. Lett.*, 187,
71–81, 2001.
- Westphal, M., Kondopoulou, D., Edel, J. B., and Pavlides, S.:
Palaeomagnetism of late Tertiary and Plio-Pleistocene forma-
tions from N. Greece, *Bull. of the Geol. Soc. of Greece*, 25, 239–
250, 1991.
- Westphal, M.: Did a large departure from the geocentric axial
dipole hypothesis occur during the Eocene?, Evidence from the
magnetic Polar wander path of Eurasia, *Earth Planet. Sci. Lett.*,
117(1-2), 15–29, 1993.